

CHOICE BETWEEN FIXED-INTERVAL SCHEDULES: GRADED VERSUS STEP-LIKE CHOICE FUNCTIONS

RICHARD L. SHULL

UNIVERSITY OF NORTH CAROLINA AT GREENSBORO

Pigeons chose between two fixed-interval schedules of food reinforcement. A single peck on one of two lighted keys started the fixed-interval schedule correlated with that key. The schedule had to be completed before the next choice opportunity. The durations of the fixed intervals were varied over conditions from 15 s to 40 s. To maximize the rate of reinforcement, the pigeons had to choose exclusively the shorter of the two schedules. Nevertheless, choice was not all-or-none. Instead, relative choice, and the rates of producing the fixed intervals, varied in a graded fashion with the disparity between the two schedules. Choice ratios under this procedure (single response to choose) were highly sensitive to the ratios of the fixed-interval schedules.

Key words: choice, reinforcement immediacy, chain schedules, maximizing, fixed-interval schedules, concurrent schedules, key peck, pigeons

Under concurrent fixed-ratio fixed-ratio schedules of reinforcement, each of two fixed-ratio (FR) schedules is correlated with a different response alternative. The response alternatives might be two lighted keys for a pigeon to peck. The pigeon gets food if it pecks the left key a fixed number of times or the right key a different fixed number of times. Different pairs of FR schedules are arranged over the course of the experiment. The point is to see how choice varies as a function of the differences between the two FR schedules.

According to several different theoretical accounts—for example, molar maximizing (Rachlin, Battalio, Kagel, & Green, 1981; Staddon, 1980), molecular maximizing (Shimp, 1969), optimal foraging (Krebs, 1978), and melioration (Herrnstein & Vaughan, 1980; Vaughan, 1981)—the pigeons should respond exclusively on whichever key has the smaller FR schedule. By choosing the smaller FR exclusively, the pigeons will emit the fewest responses per reinforcer. (Matching theory also predicts exclusive choice, but its predictions are ambiguous about which of the two schedules will be chosen; Herrnstein & Vaughan, 1980.)

The same accounts also predict all-or-none choice between pairs of variable-ratio (VR) schedules. Although the key that has the smaller response count varies from trial to trial, the

average count per reinforcement will be lowest if the smaller VR schedule is chosen exclusively.

One way to see if choice is all-or-none is to plot choice proportions as a function of the relative size of the FR (or VR) schedule. All-or-none choice implies a step-like function. That is, choice proportions would be zero for all values of relative reinforcers per response below the point of equality between the two schedules. Choice proportions would be 1.0 for all values of relative reinforcers per response above the point of equality.

Indeed, choice functions under concurrent FR FR and concurrent VR VR schedules often appear roughly step-like (Herrnstein & Loveland, 1975; Krebs, 1978; Staddon, 1980). Close examination, however, reveals that the functions actually are more S-shaped than step-shaped (see Allison, 1981, and Timberlake, 1984, for reviews; also Deluty & Church, 1978; Lea & Roper, 1977; Shapiro & Allison, 1978; Shimp, 1973). That is, choice is a graded function of the relative difference between the schedules, especially within the range of values closely surrounding the equality point.

Several factors may cause deviations from a step-like function. First, the subjects must have enough contact with the schedules for stable choice patterns to develop (Krebs, Kacelnik, & Taylor, 1978; Shimp, 1973). In one study with rats (Shapiro & Allison, 1978), the lever that had the smaller FR was changed every day or two. Perhaps one session with a particular pair of FR schedules was insufficient exposure to produce exclusive choice.

This research was supported in part by NSF Grant BNS-8519215 to The University of North Carolina at Greensboro. Correspondence and requests for reprints may be sent to Richard L. Shull, Department of Psychology, The University of North Carolina at Greensboro, Greensboro, North Carolina 27412.

Second, the use of variable schedules might promote occasional choices of the schedule with the larger average count. The prediction of exclusive choice is based on long-term average values. It is more realistic, however, to assume that the effective average weights recent events more than remote ones (Killeen, 1981; Krebs et al., 1978). If so, the effective average under the VR schedules will fluctuate depending on the response counts most recently experienced. Suppose, for example, that a subject is responding on the richer VR schedule. Because of the variability in the required response count, the subject will experience occasional lean periods that may cause the effective (recency-weighted) average of the richer VR to drop below that of the other (leaner) VR. If the subject were choosing on the basis of the effective averages, it would switch to the leaner VR at that point. Such a reversal of choice would seem inconsistent with maximizing based on the long-term average schedule values, but would be entirely consistent with maximizing based on the recency-weighted average values.

Finally, time per reinforcer after the choice rather than responses per reinforcer might be the critical dimension (Neuringer, 1969; Shull, 1979). Time per reinforcer results from how quickly the subject completes the response count, and so can vary from reinforcer to reinforcer even if the response count is constant. These variable times could produce tendencies to switch to the poorer VR or FR due to short-term fluctuations in the average, as just described.

The present study determined the form of the choice function when the alternative schedules were fixed rather than variable and time-based rather than count-based. Pigeons chose between two fixed-interval (FI) schedules in a procedure in which maximizing reinforcement rate required exclusive choice of the shorter FI. A single peck to either key during the choice period started the FI correlated with that key. Once a choice response was made, the FI had to be completed before the next choice opportunity became available.

The intent was to examine choice between FI pairs over a range near the indifference point. Thus, the FI durations differed by a ratio of 2:1 or less. Any systematic deviation from a step function should be most apparent within that range of FI-duration ratios.

METHOD

Subjects

The subjects were 3 adult male pigeons obtained from the Palmetto Pigeon Plant. Each pigeon was maintained at roughly 85% of its free-feeding weight by limiting access to food. Water and grit were continuously available in each bird's home cage. The pigeons had served previously in experiments involving the reinforcement of key pecking by access to grain, but the particular experiments differed among the birds.

Apparatus

The experimental chamber was a box (28 cm by 28 cm by 32 cm high). Three circular (1.7 cm diameter) translucent response keys were mounted horizontally on the front wall 22 cm above the floor, one in the center and the other two 7.5 cm to the left and right. Only the two side keys were used. The keys were illuminated either white or red by turning on colored lights mounted behind the keys. When lighted, a sufficiently forceful peck (at least 0.2 N) was recorded as a response. An overhead houselight located on the ceiling near the front wall provided low-level illumination throughout the experimental session. Centered below the keys, 10 cm above the floor, was a rectangular opening that gave access to mixed grain when the food hopper was raised. At those times, the feeder opening was illuminated and the keylights were darkened. All hopper presentations lasted 4 s. An externally mounted fan provided masking noise and ventilation. Electromechanical control and recording equipment was located in an adjoining room.

Procedure

Because of the pigeons' prior experience, no preliminary training was needed to establish key pecking. The pigeons were exposed directly to the experimental conditions. For the first seven conditions, sessions consisting of choice trials alternated with sessions consisting of "forced" trials, as described below.

Choice-trial sessions. At the start of each choice trial (i.e., at the beginning of a daily session and after each reinforcer), the two keys were lighted white. A single peck to either key turned the other keylight off and changed the color of the key just pecked to red. The peck also started a fixed interval of time at the end

Table 1

The order of conditions, the intended durations (in seconds) of the FI schedules in the terminal links, the average obtained terminal-link time (in seconds) for each bird, the number of choice sessions for each condition, and the choice proportions for the left terminal link over the last five choice sessions.

Condition order	Intended FI		Obtained terminal-link duration						Num- ber of ses- sions	Proportion choices left		
			3498		3349		3869					
	Left	Right	Left	Right	Left	Right	Left	Right				
1	30	30	30.79	28.77	31.94	29.80	31.33	30.93	11	.145	.240	.860
2	15	30	15.56	30.50	15.48	31.33	15.60	30.50	15	.990	.985	.990
3	30	30	28.65	30.76	30.63	30.66	30.64	30.97	25	.775	.665	.210
4	30	15	30.75	15.49	31.00	15.54	31.00	15.65	20	.020	.005	.005
5	30	20	30.67	20.60	30.73	20.56	30.50	20.99	35	.060	.015	.010
6	30	25	30.41	23.44	30.40	23.64	31.28	26.36	20	.110	.025	.090
7	30	35	30.18	35.77	30.36	35.89	30.25	36.22	30	.760	.865	.525
8	35	30	35.95	29.16	35.96	27.94	36.24	29.51	20	.210	.375	.105
9	30	35	28.85	35.88	28.85	35.95	28.80	36.45	20	.835	.780	.675
10	35	30	35.84	28.57	35.92	28.55	36.22	29.29	15	.285	.325	.180
11	30	35	28.30	36.06	28.54	35.28	28.66	36.44	20	.840	.800	.865
12	40	30	41.00	27.92	41.15	28.03	41.20	28.30	20	.160	.295	.050
13	30	40	25.41	41.25	25.82	41.00	25.84	40.82	25	.820	.870	.945
14	40	30	42.30	24.66	41.38	24.70	41.17	25.04	25	.050	.040	.030

of which a peck produced food. The end of the interval was not signaled, and pecks during the interval had no programmed consequence. Thus, each key was correlated with a different chained FR 1 FI schedule. A single peck to a white key (the FR 1 initial link) produced the red key color and the terminal-link FI schedule correlated with that key position (left vs. right).

The initial links were concurrent. That is, the two white keys were simultaneously available and either could be pecked. The terminal links, however, were not concurrently available. That is, whichever FI had been selected had to be completed before another choice became available. A new choice trial began immediately after delivery of food reinforcement. Each session lasted until 40 reinforcers had been delivered. Sessions were conducted seven days a week.

The FI durations ranged from 15 s to 40 s. A particular pair of FI schedules remained in effect for a block of consecutive sessions (a condition). The pairs were varied between conditions. Sometimes the shorter FI was correlated with the left key, sometimes with the right key. Some of the FI pairs were studied several times, with key position switched.

Under this kind of choice procedure, any choice of the longer of the two FI durations lowers the rate of reinforcement below the

maximum possible. This is so because each initial-link peck produced its corresponding terminal-link FI schedule and because the FI had to be completed before the next choice opportunity.

Table 1 lists the conditions in the order in which they were presented. Shown are the intended FI schedules for each key, the mean obtained terminal-link durations (based on the last five sessions of a condition), and the number of choice sessions. All but three conditions were studied for at least 20 choice sessions. Choice ratios usually appeared stable (no apparent systematic upward or downward trend over days) by the 10th session after a schedule change.

The calibration of one of the FI timers (the one that controlled the constant FI 30-s terminal link) gradually changed over conditions. This drift is apparent in the fact that the obtained FI for the 30-s terminal link progressively shortened over conditions from about 30 s to about 25 s. The obtained terminal-link durations are used in all analyses.

Single-chain (forced) sessions. Single-chain sessions operated exactly like choice-trial sessions except that during the initial link, only one of the keys was lighted white and effective for pecking. A single peck to that key produced its corresponding terminal-link color and FI

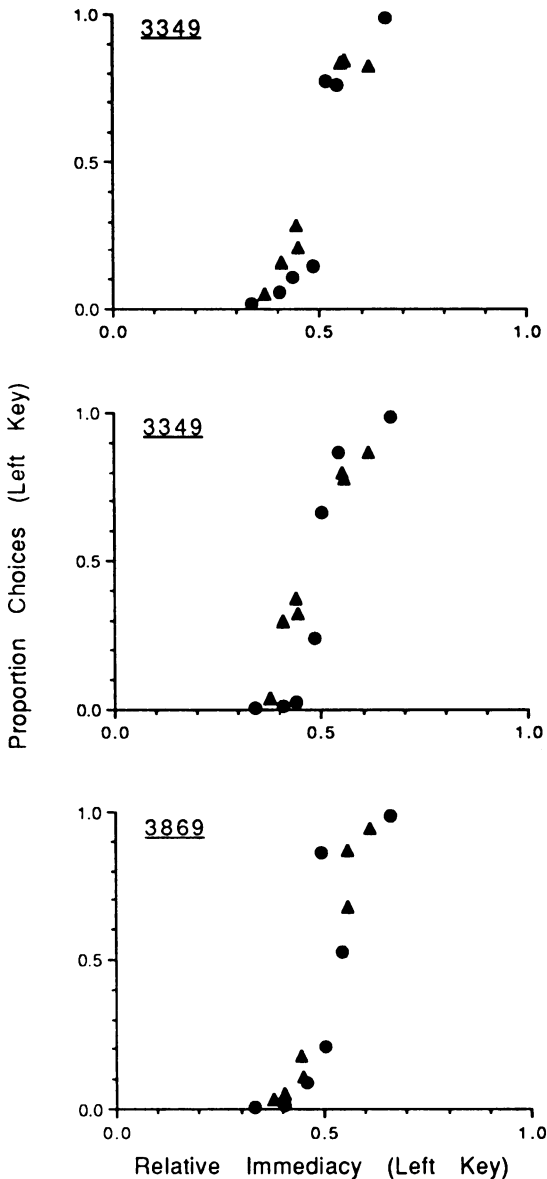


Fig. 1. The proportion of choices to the left key [$C_L / (C_L + C_R)$] plotted as a function of the relative immediacy value. The immediacy (I) is the reciprocal of the obtained delay from the onset of the terminal link until food reinforcement. The relative immediacy is $I_L / (I_L + I_R)$. Circles show data from the first seven conditions; triangles show data from the last seven conditions.

schedule, as described above. The two chained schedules were presented in strict alternation. That is, after the reinforcer from one chain, the other key was lighted white. There were 40 chain cycles per session.

Throughout the first seven conditions, choice

sessions alternated with single-chain sessions. The purpose of the single-chain sessions was to ensure that the birds had experience with both choice alternatives. The single-chain sessions were discontinued after the seventh condition.

RESULTS

Analyses of initial-link responding are based on measures summed over the last five choice sessions of each condition (200 choice trials). Initial-link response rates were calculated for each chain of the pair by dividing the number of initial-link responses in a particular chain by the time spent in the initial link. Because there was exactly one initial-link response per terminal-link entry, the number of initial-link responses is the same as the number of choices of a particular terminal-link schedule. Thus, the ratio of the initial-link response rates is identical to the ratio of choices.

The reciprocal of the obtained terminal-link duration (Table 1) was used to represent the terminal-link reinforcement. This reciprocal is the reinforcer immediacy. In the present procedure there was a single reinforcer delivery per terminal link, and that reinforcer delivery ended the terminal link. Under such conditions, the reinforcer immediacy is equivalent to the rate of reinforcement during that terminal link, when expressed relative to a common time base (e.g., per hour).

The primary interest was to see how choice varied as a function of the FI durations in the two terminal links. One way to examine this relation is to plot the proportion of choices of a particular key (left vs. right) as a function of the relative immediacy values. The relative immediacy value was calculated by the formula $I_L / (I_L + I_R)$, where I refers to the immediacy and the subscripts identify the keys (left or right). When the two terminal links are equal, this index is .5. Values below .5 indicate that the left key has the lower immediacy value (longer FI); values above .5 indicate that the left key has the higher immediacy value (shorter FI).

Figure 1 shows how the proportion of choices of the left-key terminal link varied as a function of the relative immediacy of reinforcement for that terminal link. For all 3 birds, the functions are sharply rising. Nonetheless, the functions are graded (S-shaped) rather than

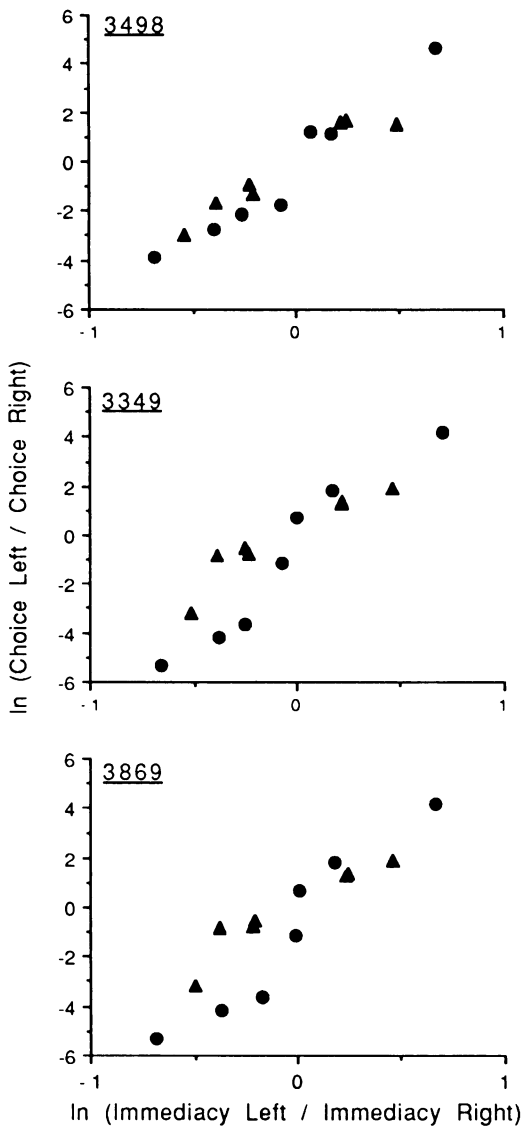


Fig. 2. The natural logarithms of the choice ratios are plotted over the natural logarithms of the ratios of the obtained reinforcer immediacies in the terminal links. Circles show data from the first seven conditions; triangles show data from the last seven conditions.

all-or-none (step-shaped). That is, the pigeons produced the poorer terminal link at least occasionally under all pairs, and the likelihood of their doing so decreased in graded fashion as the disparity between the terminal-link schedules increased. (Choice proportions are also given in Table 1.)

It may be easier to see the graded nature of the choice function if the logarithms of the choice ratios, rather than the proportion of

Table 2

The best fitting linear functions ($y = ax + b$) for the data in Figure 2 based on Pearson's least squares method. The y variable is the natural logarithm of the ratio of choices; the x variable is the natural logarithm of the ratio of reinforcer immediacies in the two terminal links. a indicates the sensitivity of choice ratios to reinforcer-immediacy ratios; b indicates bias for one key over the other, with 0 indicating no bias. The r^2 values indicate the percentage of variance accounted for by the best fitting lines. Three functions are shown for each bird. The top one is based on all 14 points, the middle one is based on the points from the first seven conditions, and the bottom one is based on the points from the last seven conditions.

Bird	Equation	r^2
3498	$y = 5.81x - 0.02$.92
	$y = 6.56x - 0.04$.94
	$y = 4.80x - 0.01$.93
3349	$y = 6.43x - 0.15$.84
	$y = 7.75x - 0.55$.93
	$y = 4.57x + 0.21$.90
3869	$y = 7.29x - 0.45$.90
	$y = 7.80x - 0.66$.91
	$y = 4.66x + 0.13$.90

choices, are plotted. Figure 2 shows the logarithm of the ratio of choices (left/right) plotted over the logarithm of the ratio of the reinforcer immediacies (left/right). In such plots, the slope of the function shows the sensitivity of choice ratios to changes in the reinforcer-immediacy ratios, and the intercept indicates bias due to extraneous factors (see Baum, 1974, and Davison & McCarthy, 1988, for discussions of these kinds of plots). (Note that the slope is the same regardless of whether natural or common logarithms are used.) In Figure 2 the trends of the points are reasonably linear over the limited range of relative and absolute terminal-link durations examined.

The slopes of the best fitting straight lines based on all 14 points ranged from 5.81 to 7.29 (see Table 2 for the results of the least squares linear fits). These values confirm that choice was very sensitive to changes in the ratio of terminal-link durations.

It seemed possible that the enforced exposure to the poorer terminal link during single-chain sessions could have enhanced the tendency to choose the poorer terminal link. During those sessions, initial-link responding occurred in the poorer chain and was reinforced. To eliminate this potential contribution, the single-chain sessions were discontin-

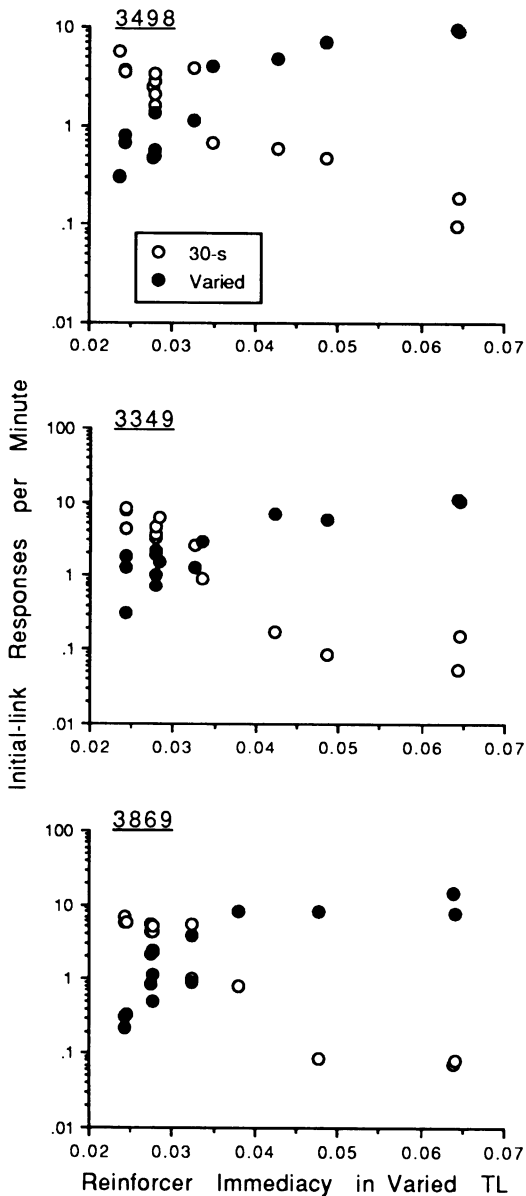


Fig. 3. Open circles: Response rate in the initial link of the chain that had the intended FI 30-s schedule in the terminal link is plotted over the obtained reinforcer immediacy in the other terminal link. Closed circles: Response rate in the initial link of the chain whose terminal link varied across conditions is plotted over the obtained reinforcer immediacy in its terminal link. Reinforcer immediacy is the reciprocal of the obtained time from the onset of the terminal link until food reinforcement.

ued after the seventh condition. There was no evidence, however, that choice became more all-or-none-like after the seventh condition (compare circles and triangles in Figure 2). Indeed, the functions based on the last seven

conditions appeared less steep than those based on the first seven (see Table 2 for the separate slopes, but note that the slopes are not strictly comparable due to differences in the range of x -axis values).

Figures 1 and 2 demonstrate an orderly relation between relative choice and terminal-link reinforcement. According to some interpretations (Catania, 1966; Herrnstein, 1970; Skinner, 1950) "choice" should be regarded as a by-product of the rates of the concurrent responses rather than as fundamental. Thus, it might be informative to determine how the terminal-link schedules influenced the absolute rates of initial-link responding in the choice procedure.

In the simplest case, one terminal-link schedule is held constant and the other is varied across conditions. Then the two initial-link response rates could be plotted as functions of the reinforcer immediacy in the varied terminal link. That way, it would be possible to determine how initial-link response rate changed as a function of reinforcer immediacy in its own terminal link, with the alternative reinforcement held constant. Also, it would be possible to see how initial-link responding for a constant terminal link varied as a function of alternative reinforcement.

The intent of the design was to carry out such an analysis. Because of the timer calibration problem, however, the schedule that was supposed to be FI 30 s throughout the experiment became progressively shorter. Nonetheless, it seemed worthwhile to plot the response-rate functions as if one of the terminal links had remained constant across conditions. The discrepancies between intended and obtained terminal-link intervals seemed unlikely to be large enough to distort the functions in a way that would compromise their interpretation.

Figure 3 shows these functions for the choice sessions. The logarithmic scaling was used to reveal possible trends at low response rates. Open points show initial-link response rates for the chain with the intended FI 30-s schedule in the terminal link. For the conditions in which both terminal-link schedules were FI 30 s, the response rate from the left key was arbitrarily selected to be included in the open-point function. Closed points show initial-link response rates for the chain that had different FI schedules correlated with the terminal link.

Initial-link response rate increased as a

function of the reinforcer immediacy in its terminal link (closed circles) and decreased as a function of the reinforcer immediacy in the alternative terminal link (open circles). Both response rate functions changed, in graded fashion, over at least 1.5 orders of magnitude. The lowest rates are about 0.1 responses per minute—that is, about one response every 6 min of initial-link time. (The difference between intended and obtained FI durations was largest under the last two conditions, represented by two of the left-most points. Thus, at the far left, two of the open points might be higher than they would have been if the schedule had been FI 30 s as intended, and two of the closed points might be lower than they would have been.)

There is, of course, a necessary correspondence between the choice-ratio function and the relative difference between the two initial-link response-rate functions. It is possible, then, that the trends seen in the two initial-link response-rate functions are consequences of changes in the choice ratios. It is also possible, however, that the changes in choice ratios are consequences of the changes in the two initial-link response rates. In any case, the absolute levels of initial-link response rates are unconstrained by the choice ratios, so Figure 3 provides information not contained in Figures 1 and 2.

DISCUSSION

Under the present procedure, any response that produced the longer of the two FI schedules reduced the rate of reinforcement below the maximum. Nevertheless, there was some tendency to produce the longer FI under all choice pairs. Further, this tendency was a graded function of the difference between the two FI schedules.

There are several possible reasons for the functions being graded. One class of reasons considers the deviations from exclusive choice as the result of insufficient control over relevant environmental factors. Variability in duration of the terminal-link schedules was eliminated as a factor by using fixed-duration (FI) schedules in the terminal links. But there are other environmental factors that could have been influential.

First, the number of responses per reinforcement varied, even though the terminal-link time was constant. As discussed above,

perhaps variability in the obtained response count produced fluctuations in a recency-weighted average schedule value that caused preference to switch from time to time.

Second, perhaps if more sessions had been run at each condition, choice eventually would have become all-or-none. Although that possibility cannot be ruled out, it is worth noting that the exposure was well within the normal range for choice studies. All but three conditions were run for at least 20 choice-trial sessions of 40 trials each. Additional exposure during the first seven conditions came from the single-chain sessions. Indeed, performance usually appeared to have reached asymptote by the 10th session after a schedule change.

Third, stimulus factors might have contributed to the deviations from a step function. The two keys during the initial links were distinguished by location but had some stimulus features in common. For example, both were white and round. Also, the keys for both terminal links were both red. Perhaps responding in the initial link of the poorer chain was an instance of stimulus generalization. That is, response tendencies conditioned to the initial-link stimulus in the better chain might have generalized to the initial-link stimulus in the poorer chain due to control by stimulus features common to both initial links. If so, making the initial-link alternatives more distinct should produce functions that are more nearly step-like.

A different class of reasons for the graded choice functions derives from the possibility that even under ideal environmental control, variability is still inevitable in a biological system. Such biological variability has been acknowledged in many different theoretical approaches. One approach emphasizes the role of natural selection in producing a tendency to sample alternatives (Krebs, 1978; Krebs et al., 1978; Timberlake, 1984; Zeiler, 1987; see also Hackenberg & Hineline, 1992). In nature, a patch that an animal has depleted by foraging may be replenished and become better than the current patch. Animals who tend to sample, it is argued, will be able to exploit an improved patch. Such tendencies may have been favored by natural selection. Sampling will tend to occur, then, whether or not such sampling is immediately adaptive.

A second approach has been to assume that environmental events generate internal events that, in turn, control behavior. The internal

mediating events (which may be interpreted as covert behavior or physiological events) are variable even if the initiating environmental event is constant (Green & Swets, 1966). If one were to take that approach, the FI terminal links would be interpreted as inevitably functioning as variable-interval schedules (Gibbon, 1977; Gibbon, Church, Fairhurst, & Kacelnik, 1988). Nonexclusive choice, then, could be understood as due to short-term fluctuations in the effective average, as described above for true variable schedules.

A third approach to acknowledging intrinsic variability in a biological system is to treat operant behavior as fundamentally probabilistic or stochastic (Bush & Mosteller, 1955; cf. Staddon & Horner, 1989). The suggestion that operant behavior is emitted implies such a treatment (Skinner, 1950). The variables that affect emission rate (or probability) can be examined without making any inferences about the internal physiological events that are the immediate causes of particular emissions. The emission rate may be found to vary as a function of molar environmental factors, including past reinforcement. Choice might best be regarded as a by-product of the emission rates of two (or more) concurrently available responses (Catania, 1966; Herrnstein, 1970; Skinner, 1950).

Applied to the present results, the occasional choices of the longer FI can be understood as a consequence of an above-zero emission rate due, perhaps, to the reinforcement of the initial-link response by the terminal link. From this view, the absolute initial-link response-rate functions (Figure 3) would be considered more fundamental than the choice functions (Figures 1 and 2).

REFERENCES

- Allison, J. (1981). Paired baseline performance as a behavioral ideal. *Journal of the Experimental Analysis of Behavior*, **35**, 355-366.
- Baum, W. M. (1974). On two types of deviations from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior*, **22**, 231-242.
- Bush, R. R., & Mosteller, F. A. (1955). *Stochastic models for learning*. New York: Wiley.
- Catania, A. C. (1966). Concurrent operants. In W. K. Honig (Ed.), *Operant behavior: Areas of research and application* (pp. 213-270). New York: Appleton-Century-Crofts.
- Davison, M., & McCarthy, D. (1988). *The matching law: A research review*. Hillsdale, NJ: Erlbaum.
- Deluty, M. Z., & Church, R. M. (1978). Time-allocation matching between punishing situations. *Journal of the Experimental Analysis of Behavior*, **29**, 191-198.
- Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, **84**, 279-325.
- Gibbon, J., Church, R. M., Fairhurst, S., & Kacelnik, A. (1988). Scalar expectancy theory and choice between delayed rewards. *Psychological Review*, **95**, 102-114.
- Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.
- Hackenberg, T. D., & Hineline, P. N. (1992). Choice in situations of time-based diminishing returns: Immediate versus delayed consequences of action. *Journal of the Experimental Analysis of Behavior*, **57**, 67-80.
- Herrnstein, R. J. (1970). On the law of effect. *Journal of the Experimental Analysis of Behavior*, **13**, 243-266.
- Herrnstein, R. J., & Loveland, D. H. (1975). Maximizing and matching on concurrent ratio schedules. *Journal of the Experimental Analysis of Behavior*, **24**, 107-116.
- Herrnstein, R. J., & Vaughan, W., Jr. (1980). Melioration and behavior allocation. In J. E. R. Staddon (Ed.), *Limits to action: The allocation of individual behavior* (pp. 143-176). New York: Academic Press.
- Killeen, P. R. (1981). Averaging theory. In C. M. Bradshaw, E. Szabadi, & C. F. Lowe (Eds.), *Quantification of steady-state operant behavior* (pp. 21-34). Amsterdam: Elsevier.
- Krebs, J. R. (1978). Optimal foraging: Decision rules for predators. In J. R. Krebs & N. B. Davies (Eds.), *Behavioural ecology: An evolutionary approach* (pp. 23-63). Oxford: Blackwell.
- Krebs, J. R., Kacelnik, A., & Taylor, P. (1978). Tests of optimal sampling by foraging great tits. *Nature*, **275**, 27-31.
- Lea, S. E. G., & Roper, T. J. (1977). Demand for food on fixed-ratio schedules as a function of the quality of concurrently available reinforcement. *Journal of the Experimental Analysis of Behavior*, **27**, 371-380.
- Neuringer, A. J. (1969). Delayed reinforcement versus reinforcement after a fixed interval. *Journal of the Experimental Analysis of Behavior*, **12**, 375-383.
- Rachlin, H., Battalio, R. C., Kagel, J. H., & Green, L. (1981). Maximization theory in behavioral psychology. *Behavioral and Brain Sciences*, **4**, 371-388.
- Shapiro, N., & Allison, J. (1978). Conservation, choice, and the concurrent fixed-ratio schedule. *Journal of the Experimental Analysis of Behavior*, **29**, 211-223.
- Shimp, C. P. (1969). Optimal behavior in free-operant experiments. *Psychological Review*, **76**, 97-112.
- Shimp, C. P. (1973). Probabilistic discrimination learning in the pigeon. *Journal of Experimental Psychology*, **97**, 292-304.
- Shull, R. L. (1979). The postreinforcement pause: Some implications for the correlational law of effect. In M. D. Zeiler & P. Harzem (Eds.), *Advances in analysis of behavior. Vol. 1: Reinforcement and the organization of behavior* (pp. 193-231). Chichester, England: Wiley.
- Skinner, B. F. (1950). Are theories of learning necessary? *Psychological Review*, **57**, 193-216.
- Staddon, J. E. R. (1980). Optimality analyses of operant behavior and their relation to optimal foraging. In J. E. R. Staddon (Ed.), *Limits to action: The allocation of individual behavior* (pp. 101-141). New York: Academic Press.

- Staddon, J. E. R., & Horner, J. M. (1989). Stochastic choice models: A comparison between Bush-Mosteller and a source-independent reward-following model. *Journal of the Experimental Analysis of Behavior*, **52**, 57–64.
- Timberlake, W. (1984). Behavior regulation and learned performance: Some misapprehensions and disagreements. *Journal of the Experimental Analysis of Behavior*, **41**, 355–375.
- Vaughan, W., Jr. (1981). Melioration, matching, and maximizing. *Journal of the Experimental Analysis of Behavior*, **36**, 141–149.
- Zeiler, M. D. (1987). On optimal choice strategies. *Journal of Experimental Psychology: Animal Behavior Processes*, **13**, 31–39.

Received July 17, 1991

Final acceptance January 14, 1992